

**EROSION RATES ON MARS AND
IMPLICATIONS FOR CLIMATE CHANGE:
CONSTRAINTS FROM THE PATHFINDER LANDING SITE**

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ABSTRACT

The observation that the Mars Pathfinder landing site looks very similar to its appearance after it was deposited by catastrophic floods some 1.8-3.5 Ga allows quantitative constraints to be placed on the rate of change of the site since that time. The abundance of erosional features such as an exhumed former soil horizon, sculpted wind tails, ripplelike and other lag deposits, and ventifacts (fluted and grooved rocks) all suggest the site has undergone net deflation or loss of 3-7 cm of material. The presence of barchan dunes and ventifacts argues for erosion by saltating crystalline sand-size particles entrained in the wind. Most ventifacts probably formed soon after the catastrophic flood, which likely introduced a large, fresh supply of sand-size particles distributed across the rocky plain. The strongest winds blew towards the northwest during this time, resulting in the sculpting of ventifacts, deflation of the surface, the collections of dunes within Big Crater and other lows, and possibly preferentially eroding small crater rims. The predominant wind direction changed to blow towards the southwest, similar to today. These winds further deflated the surface, completed the deposition of sand-size material in dunes and ultimately trapped these dunes in lows. The erosional features observed by Pathfinder indicate extremely low long term deflation rates of 0.01-0.04 nm/yr since the end of the Hesperian (1.8-3.5 Ga) similar to less precise rates of <1 nm/yr based on the preservation of craters at the Viking 1 and Pathfinder landing sites. Short term redistribution rates (deposition and removal) of atmospheric dust at the Pathfinder landing site and pre-existing dust and sand at other locations on Mars are up to 10^5 nm/yr. Estimates of erosion rates on Mars show a rapid decrease by 3-6 orders of magnitude from 10^2 - 10^4 nm/yr in Noachian terrains (characterized by rimless, flat-floored craters and valley networks) to the exceedingly slow rates (10^{-2} - 10^{-1} nm/yr) operating during the Hesperian and Amazonian. Noachian erosion rates comparable to low continental denudation rates on the Earth are consistent with erosion by running water and perhaps a more clement climate. The rapid decrease in erosion rates is consistent with a major climatic change during the Noachian, at the tail end of heavy bombardment, and a cold, dry, desiccating climate similar to today's since that time.

INTRODUCTION

The geomorphology of a landscape characterized by erosional and depositional features results from the nature and vigor of weathering and erosional processes. These processes are, in turn, related to the climatic and environmental conditions that have acted on the surface. At the Pathfinder site, the removal, deposition, and net transport of material can be determined from the wide variety of aeolian features present. These provide insight into weathering rates and processes over the history of the Ares Valles region and Mars in general. The modification of the Martian landscape throughout the Amazonian and most of the Hesperian has been estimated to be relatively minor based on the preservation and freshness of craters and other features at the Viking landing sites and from Viking Orbiter images of young surfaces [Arvidson *et al.*, 1979; Carr, 1996]. In contrast, Noachian regions in Viking orbiter images appear to be much more degraded and eroded [Carr, 1996; Schultz and Britt, 1986]. In particular, many large Noachian craters are rimless and have shallow flat floors, suggesting that they have been eroded and filled in by sediment [Craddock and Maxwell, 1993; Craddock *et al.*, 1997; Barlow, 1995; Grant and Schultz, 1993]. Valley networks in Noachian terrain also suggest relatively high erosion rates in the past. These observations have been used to support erosion by liquid water and a possibly warmer and wetter environment [e.g., Baker *et al.*, 1992; Carr, 1996; Baker and Partridge, 1986].

The observation that the Mars Pathfinder landing site looks very similar to how it looked after deposition by catastrophic floods some 1.8-3.5 Ga [Golombek *et al.*, 1997b; Smith *et al.*, 1997; Ward *et al.*, 1999] allows quantitative constraints to be placed on the long term rate of change since that time [Golombek, 1999a]. Specifically, the landing site has a rich variety of geomorphic features that can be used to estimate the rate of change at the site, which can, in turn, be used to infer climatic conditions. When combined with interpretations of other data from Pathfinder and Global Surveyor together with perspectives drawn from 20 years of analysis and interpretation of Viking data, these observations and inferences suggest an early warmer and wetter environment with vastly different erosion rates, followed by a major climatic change. In

this paper, we describe the landforms at the Mars Pathfinder landing site and the nature of the environmental conditions that produced them, estimate the rate of change at the site, compare these rates with those estimated elsewhere and throughout time on Mars, and discuss these constraints in terms of climate change.

GEOMORPHOLOGY OF THE LANDING SITE

Prior to landing, remote sensing of the Pathfinder landing site (generally at a scale greater than ~1 km) and Earth analog studies correctly predicted the nature and characteristics of the site [Golombek *et al.*, 1997a, 1997b, 1999]. Based on its location downstream from the mouths of Ares and Tiu Valles outflow channels, the Pathfinder landing site was interpreted as being composed of materials deposited by catastrophic floods and the thermal inertia and albedo suggested it would be less dusty than either of the Viking sites. The surface imaged by the lander is made up of subangular to subrounded pebbles, cobbles, and boulders and generally resembles depositional surfaces produced by terrestrial catastrophic floods, such as the Ephrata Fan in the Channeled Scabland of Washington State [Golombek *et al.*, 1997a, 1999]. In addition, the site appears less dusty and has more dark rocks and other dark materials than the Viking sites [Golombek *et al.*, 1999; Larsen *et al.*, 1999; Bell *et al.*, this issue]. From the lander, hills 1 km to the southwest (the Twin Peaks) look like streamlined islands, consistent with interpretations of Viking Orbiter images of the region. The lander is on the flank of a broad, gentle ridge, interpreted to be a debris tail trending northeast from Twin Peaks. Rocks about 8 m southwest of the lander (called the Rock Garden) are inclined to the north and appear imbricated in the direction of flooding [Smith *et al.*, 1997]. Troughs visible throughout the scene may be primary features produced by the flood or they may result from the late-stage drainage of water after deposition, which preferentially carried away fine material, leaving a blocky armored surface behind (analogous to channels and surfaces present on the Ephrata Fan) [Golombek *et al.*, 1997b]. This general similarity to analogous surfaces on Earth argues that the site has undergone minor alteration [Golombek *et al.*, 1999; Ward *et al.*, 1999] since it formed in Late Hesperian/Early

Amazonian time [Parker and Rice, 1997], estimated at 1.8-3.5 Ga [Tanaka, 1986] based on the crater time scales of Neukum and Wise [1976] and Hartmann *et al.* [1981].

Aeolian Features and Environment from the Lander

Any natural surface can be considered to fall into one of three geomorphic categories, 1) net accumulation, 2) net deflation, or 3) no change. The last possibility is rare and depends in part on scale. For example, the regional geomorphology of the Pathfinder site, as just described, indicates that any changes, whether they be from accumulation or deflation, are minimal. The question then arises, can evidence for small degrees of change be found by studying the local geomorphology of the site? An abundance of features at the Pathfinder site indicate a minor amount of net deflation or loss of material. These include a possible exhumed former soil horizon, sculpted wind tails, ripplelike and other lag deposits, and ventifacts [Smith *et al.*, 1997; Bridges *et al.*, 1999a; Greeley *et al.*, 1999; Greeley *et al.*, this issue].

A 5-7 cm thick reddish band along the base of several rocks could be a former soil horizon that has been deflated or exhumed by the wind since deposition (Figure 1), an interpretation advocated by a number of workers [Smith *et al.*, 1997; Greeley *et al.*, 1999]. The location of the band on a number of large rocks at the site and the presence of bright bands at the base of smaller rocks [Greeley *et al.*, 1999; Kraft and Greeley, 1999a and b] argue that it is an exhumed soil horizon. No horizontal banding is found higher on rocks. Red clumps of material found on the upper surfaces and within pits of rocks have a different appearance and are almost certainly airfall dust. Without some cementing agent, such as water, it is not clear how a dust layer could be deposited that would preferentially stick to the lower horizons of rocks, suggesting that the soil horizon dates back to the flood. Remnant soil and pebble layers are also stranded on the edges of some rocks. For example, Figure 2 shows the rock Ender, about 4 m from the lander with a bright soil and pebble layer that is up to 7 cm above the present surrounding soil surface. All these observations support the interpretation that a few centimeters of deflation has occurred. Other possibilities, such as post-flood frost heaving of the rocks, cannot be completely discounted, but seem less likely. If the reddish bands do not represent soil horizons, then an

even smaller degree of deflation is suggested, implying that the 5-7 cm represents the maximum observed.

Ripplelike features at the site are interpreted as a lag deposit of small granules or pebbles (Figure 3) that may have been transported a short distance and left behind after erosion of sand and smaller size material by the wind [Greeley *et al.*, 1999]. Based on the appearance of materials in rover trenches within Mermaid Dune, at least some of the duneforms appear to be composed of poorly sorted material beneath an armoring veneer of dark gray granules. This indicates they are lag deposits [Rover Team, 1997; Moore *et al.*, 1999] resulting from net erosion or loss of material at the landing site. The sculpted shape and sharp edges of numerous wind tails behind rocks and pebbles (Figure 4) also suggests they are predominantly erosional as opposed to the bulbous shape expected of wind tails formed by deposition [Greeley *et al.*, 1999]. In this interpretation, the wind tails are the remnants of a more areally extensive deposit up to 3 cm thick that has been removed. Because the wind tails lie on top of the ripplelike lag deposit at some locations (e.g., Figure 4), this provides evidence for two periods of deflation at the landing site separated by a period of deposition of aeolian material composing the wind tails [Kraft and Greeley, 1999b]. The direction of the wind tails towards the southwest is interpreted as the direction of the wind, which agrees with the direction of bright wind streaks in Viking Orbiter images and the current direction of the strongest winds in atmospheric circulation models [see discussion in Greeley *et al.*, 1999].

The presence of ventifacts, or aeolian fluted and grooved rocks, also argues for erosion by saltating crystalline sand-size particles entrained in the wind [Bridges *et al.*, 1999a]. The ventifacts exhibit pits on their sides that transition to elongated flutes on their upper flanks to long grooves on their top surfaces (Figure 5). They appear very similar to terrestrial analogs [Bridges *et al.*, 1999a; Greeley *et al.*, 1999] and are indicative of an abrasive process oriented nearly parallel to the ground surface. The long-axes of the flutes and grooves show a general northwest orientation, characteristic of a directionally-controlled process that is different than the current, dominantly southwest blowing winds [Smith *et al.*, 1997; Greeley *et al.*, 1999]. Although

ventifact formation by windblown snow has been documented [*Dietrich, 1977; Whitney, 1978; Whitney and Spletstoeser, 1982; Schlyter, 1994*] and abrasion by dust, silt [*Whitney and Dietrich, 1973; Whitney, 1979; Schlyter, 1994*], or even air molecules have been advocated [*Whitney, 1979*] in particular areas on Earth, sand-size grains moved by saltation are far more efficient than these abrasive agents in eroding rock surfaces [*Greeley and Iversen, 1985*]. Although dust may be effective at producing pits by reverse flow on the downwind side of rocks [*Whitney and Dietrich, 1973*], it has not been shown that dust is capable of forming flutes and grooves like those seen at the Pathfinder site. In addition, the greater abundance of ventifacts at the Pathfinder site relative to the Viking lander sites [*Bridges et al., 1999a, b*] argues that the Pathfinder ventifacts formed by aeolian-transported sand derived from a local supply. The immaturity of the ventifacts and their generally different wind orientation from other aeolian features suggests that many of them may have formed early when the supply of sand-size particles was greater [e.g., *Bridges et al., 1999a; Greeley et al., this issue; Kraft and Greeley, 1999a*]. A likely source for the sand was the sediments locally deposited by the Ares and Tiu Valles floods. In contrast, aeolian depositional features at the Pathfinder site are limited to a few duneforms. Barchan-shaped features imaged by the rover (Figure 6) are asymmetric, crescent-shaped features up to 15 cm high that display "horns" projecting south-southwest to southwest, in the downwind direction. A barchanoid duneform, Jenkins, is interpreted to be a precursor duneform to a barchan [*Greeley et al., 1999*]. The barchans strongly argue for formation by saltating sand-size grains. The small number of barchan dunes at the landing site suggests they are predominantly composed of redistributed, locally derived sand-size material. A climatic regime in which saltation friction speeds were reached more frequently and the proposed local sand source were probably responsible for forming most of the ventifacts, deflating the surface, and perhaps for collecting the sand into dunes (see later discussion). This implies that the abundance of sand and the ability of winds to harness sand has decreased with time.

Aeolian Features and Environment from Orbit

Orbital images of the Pathfinder landing site reveal a surface that has been affected by the deposition, erosion, and movement of material. Within roughly 25 km of the landing site, Viking images show streamlined wakes in the lee of knobs and crater rims and linear textures oriented north-northeast to northwest. These features almost certainly formed by flood waters discharged from the Tiu (north-northeast orientation) and Ares (north to northwest orientation) Valles outflow channels [Komatsu and Baker, 1997; Rice and Edgett, 1997]. In addition to the prominent southwest oriented bright wind streaks in Viking images [Greeley *et al.*, 1999], very faint, dark linear streaks less than 200 m wide and up to 5 km long or more oriented northwest are also observed near the landing site. These have a similar appearance to wind streaks emanating northwestward from craters within a field of secondaries ~50 km southeast of the landing site. The association of these streaks with the secondaries and their dark tone indicates that they are sandy or rocky surfaces from which bright dust has been deflated by northwestward-directed winds in the lee of crater rims. The streaks that have no associated secondaries may be behind small obstacles that are below the limit of resolution or former obstacles that have eroded away.

Greeley *et al.* [this issue] interpret a prominent northwest-southeast fabric in a high-resolution (effectively ~5 m/pixel due to haze) Mars Orbiter Camera (MOC) image of the Pathfinder landing site (Figure 7) as aeolian in origin. This fabric is produced by bright sinuous ridges that are tens to hundreds of meters long, 5-20 m wide and spaced 20-60 m apart. The observation that some of the bright ridges appear to cross crater rims and interiors and drape over older flood related features such as the Twin Peaks is used to argue that the ridges are aeolian, deposited as transverse dunes in the present southwest blowing wind regime [Greeley *et al.*, this issue]. Alternatively, the ridges could be an older fluvial fabric oriented toward the northwest from Ares Valles [e.g., Parker and Rice, 1997], which would explain the common truncation of ridges by craters. This interpretation is supported by detailed topographic maps of the landing site [Kirk *et al.*, 1999] that show boulder trains, ridges, and troughs oriented northeast with relief of 1-2 m, similar to the fabric seen in the MOC and Viking images, that almost certainly must be

fluvial in origin. It is possible that the ridges result from a combination of processes in which earlier fluvial features have subsequently been modified and augmented by aeolian deposits.

Greeley et al. [this issue] also note that many of the small craters have degraded or missing west-northwest rims, although this may be an effect of the high sun angle and lighting geometry. If the craters do have degraded rims, they were likely eroded by earlier winds blowing towards the southeast or possibly the northwest (many of the ventifacts and the possible dark wind streaks in Viking images were produced by winds blowing towards the northwest). Winds of this orientation also appear responsible for the relatively thin northeast-southwest oriented dunes in Big Crater, 2 km southeast of the Pathfinder lander (Figure 7). In summary, interpretations of orbiter images of the Pathfinder landing region have been used to suggest: (1) that the west-northwest rims of small crater may have been preferentially eroded, (2) that 1-2 m thick dunes may be common, or (3) that these features may reflect an earlier fluvial period. Regardless of the interpretation, the putative erosion and/or redistribution of aeolian material is limited to changes of several meters thickness during the Amazonian epoch.

EROSION RATES

The depth of deflation at the site can be used to calculate the deflation rates since the surface formed some 1.8-3.5 Ga, which provides an estimate of the efficiency of erosional processes on Mars in Amazonian time (since the Hesperian). The 5-7 cm thick deflated soil horizon and the 3 cm thick wind tails suggest extremely low (0.01-0.04 nm/yr) deflation rates. These rates are long term averages since the surface formed at the beginning of the Amazonian, and do not account for short term depositional and erosion episodes.

Comparing small crater rim heights imaged by the lander with those expected for fresh Martian craters places similar, albeit less precise constraints on erosion rates. Big and Little (1 km to the east-southeast) Craters in view of the lander have rim heights of 40 m and 5.2 m, respectively, which are similar to the expected heights (56 m and 6 m) for fresh Martian craters with diameters of 1.5 km and 0.15 km [*Pike and Davis, 1984*]. The differences between the measured and expected heights of these craters are not statistically distinct, given the measured

dispersion of fresh crater rim heights [Pike and Davis, 1984]. The freshness of these craters in orbiter images similarly argues for little or no erosion of their rims. If the craters are not significantly younger than the surface, this limits erosion at the Pathfinder site to <1 nm/yr, which is the same result determined from crater rim heights at the Viking 1 landing site [Arvidson *et al.*, 1979]. Higher erosion rates are permissible if the craters are much younger than the surface, but the existence of dunes inside Big Crater apparently formed in the older, northwest blowing wind direction argues against this. If the west-northwest sectors of small crater rims (roughly the diameter of Little Crater or smaller) have been eroded by earlier winds at the Pathfinder site as suggested by Greeley *et al.* [this issue], rough calculations suggest there may have been the equivalent of order 1 cm erosion (distributed over the region), which corresponds to erosion rates of <0.01 nm/yr.

The amount of rock lost to ventifact abrasion at the Pathfinder landing site can be roughly estimated. About half the rocks at the landing site have been abraded [Bridges *et al.*, 1999a], with an average of about 5% area of each rock exhibiting flutes and grooves. Sojourner images of the rock Flat Top show grooves in profile that are as deep as 2 cm or more. If the average depth of abrasion for sculpted parts of rocks is 1 cm, then the average amount of abrasion on ventifacted rocks is 0.5 mm (0.05×1 cm) or, because half of the rocks appear to be ventifacts, 0.25 mm for all rocks ($0.05 \times 0.5 \times 1$ cm). Over 1.8-3.5 billion years, this translates into an erosion rate of 7×10^{-5} - 1×10^{-4} nm/yr. In contrast, experimental simulations of rock abrasion at the Viking 1 site on Mars predict erosion rates 7.7 to 210 $\mu\text{m}/\text{yr}$ in the presence of an abundant supply of sand-size particles [Greeley *et al.*, 1982; 1985], which are slightly greater than rates on Earth [Greeley *et al.*, 1985]. If the ventifacts actually formed at these experimentally simulated rates, then the ventifacts at the Pathfinder site would have been carved in a very short 1.2-32.5 yr. Abrasion at this rate would also erode away small craters and other small topographic features in geologically short periods of time, which has obviously not occurred. A limited sand supply on Mars today can explain the discrepancy between the erosion rates predicted by these experiments and those estimated from the geomorphology and inferred age of the surface [Greeley *et al.*, 1982, 1985]. It

seems most likely that most ventifact sculpting occurred over a geologically short period of time, perhaps after catastrophic flooding deposited a fresh, abundant supply of sand-size material. If the ventifacts formed over an interval of, say 2.5 to 25 million years, then abrasion rates are 0.01-0.1 nm/yr, typical of the other Amazonian erosion rates reported herein. This discussion suggests that rock abrasion under Amazonian-era erosion rates can only occur if supplies of sand are abundant, or climatic conditions were such that threshold friction speeds were reached more frequently than they are today, facilitating rock abrasion. Regardless of whether the ventifacts formed over a brief time interval shortly after flooding, as seems likely, or were sculpted progressively over time, the erosion rates they imply agree with the lack of change at the Pathfinder landing site in Amazonian time.

Short term redistribution of material may be occurring at higher rates than the long term rates calculated above. Bright dust was found in the atmosphere, coated many rocks at the Pathfinder landing site, and appeared to settle from the atmosphere during the mission [*Smith et al.*, 1997; *Rover Team*, 1997]. The solar panels of the lander and rover experienced a decrease in power generation with time and the materials adherence experiment on the rover estimated the dust accumulation at 0.28% per day [*Rover Team*, 1997]. Depending on the size and shape of the dust [*Tomasko et al.*, 1999], this translates into a rate of dust deposition of 5-15 $\mu\text{m}/\text{yr}$ [*Landis and Jenkins*, 1998, this issue]. Rates such as these cannot represent long term averages as such rates would result in meters thick accumulations of dust within a comparatively short span of a million years. Dust devils observed by Pathfinder [*Schofield et al.*, 1997; *Metzger et al.*, 1999] or some other process must remove dust from the surface over relatively short time scales. The 15 cm high barchan dunes (Figure 6) observed at the Pathfinder landing site [*Greeley et al.*, 1999] also likely represent redistribution of material, rather than deposition of new material. These features and the wind tails, if they are actually depositional features (contrary to the favored interpretation) suggest rates of formation of $<0.1 \text{ nm}/\text{yr}$.

Our preferred interpretation of these results is that overall there has been net removal and deflation of about 3-7 cm of aeolian material from the Mars Pathfinder landing site, with some

redistribution of material into aeolian dunes. Rock abrasion may have been higher in the past to produce many of the ventifacts immediately following catastrophic flooding, which likely introduced a large, fresh supply of sand-size particles, which deflated the surface. It is possible that multiple episodes of burial and deflation may have occurred as the possible dunes identified in the MOC image may have migrated through the region [*Greeley et al.*, this issue] and perhaps deposited aeolian material on ripplelike lag surfaces that were later cut into wind tails [*Kraft and Greeley*, 1999b]. Erosion of 3-7 cm of material from the Pathfinder region can easily account for any subsequent deposition of aeolian material as the volume of material eroded is 2-5 times greater than the volume of material needed to form the observed (in lander images) and putative (in orbiter images) duneforms. In summary, these observations and calculations severely limit the erosion or deflation of materials at the Pathfinder landing site to <0.1 nm/yr or <0.1 mm/Ma or <0.1 m/Ga in the past 1.8-3.5 Ga and suggest that a cold and dry environment, similar to today's, has prevailed since that time.

DISCUSSION

Environments at the Pathfinder Site

A large supply and flux of sand-size particles are implied for the Pathfinder landing site soon after flooding. Freshly deposited sand was likely extensive and mobile, resulting in a broad particle size distribution (an important factor controlling aeolian abrasion) ranging from micron-scale dust to pebbles to rocks and boulders. The relative effects of wind strength and frequency cannot be easily separated, as short periods of sustained, strong winds versus longer periods of gusty winds that periodically reached threshold could both have entrained significant amounts of sand and may have been operative. The strongest winds blew towards the northwest during this period to produce the ventifacts, the northeast-southwest oriented dunes inside Big Crater, and perhaps the faint, dark wind streaks observed in Viking Orbiter images and the eroded west-northwest sectors of crater rims [*Greeley et al.*, this issue]. If the putative eroded west-northwest sectors of crater rims were eroded by winds blowing towards the northwest, erosion was focused on the lee side of the crater rims; alternatively they were eroded by winds blowing towards the

southeast [*Greeley et al.*, this issue]. Sand-size material may have begun to collect into dunes and become trapped in lows at this time. It is likely that saltation of sand during this period was erosive, as indicated by the ventifacts and produced much of the deflation and the ripplelike lag deposit observed [*Kraft and Greeley*, 1999b].

After this period, the strongest wind directions changed to blow towards the southwest, similar to today. Winds in this direction are responsible for creating the wind tails and for orienting the sand dunes. The Pathfinder landing site today likely has a limited flux of particles, due both to a low supply and winds that may rarely reach threshold. Although sand is present, it seems confined to a few duneforms and trapped within depressions and is not as broadly distributed as it was in the early regime. Because sand appears segregated to specific locations and because many parts of the site have been deflated, particle size distributions are variable, consisting of either unimodal sand, unimodal dust or silt-sized grains, or poorly sorted mixtures. The strongest winds blow towards the southwest, which agrees with the direction of bright wind streaks in Viking Orbiter images and the current direction of the strongest winds in atmospheric circulation models with weaker winds from other directions. These winds may redistribute dust and slowly deflate the surface, but do not move sand or abrade rocks to a significant degree. If the bright streaks in the MOC image are actually sand dunes as interpreted by *Greeley et al.* [this issue] they argue that some sand in the area may not be trapped and could still be harnessed by the wind if wind speeds are high enough.

Martian Surface Layer

The role that sand has played in the erosion of the Pathfinder landing site and the Martian surface in general was probably much greater in the past than it is today. The importance of sand in Martian weathering processes involves: 1) the rate of sand production, 2) the rate of sand destruction, 3) the rate of sand trapping, and 4) changes in the threshold friction speed over time. Most sand on Earth has formed via water dominated weathering, erosional, and depositional processes that mechanically break down rocks into smaller fragments [*Kuenen*, 1960; *Krinsley and Smalley*, 1972; *Pettijohn et al.*, 1987; *Smalley and Krinsley*, 1979]. During the dry

Amazonian, sand formation has probably been relatively slow, limited to impact, volcanic, and mechanical weathering processes. The high velocity and kinetic energy of saltating sand under current Martian threshold friction speeds may cause its destruction as it abrades rock surfaces [Sagan *et al.*, 1977; Greeley, 1979; Krinsley *et al.*, 1979; Greeley *et al.*, 1982]. Sand that is not destroyed in “kamikaze” collisions will saltate across the surface until it is trapped in craters or other depressions shielded from regional winds [Breed *et al.*, 1979]. As discussed earlier, sand is most likely present at the Pathfinder landing site and trapped sand appears abundant elsewhere on Mars both at the scale of Viking [Breed *et al.*, 1979] and Global Surveyor [Malin *et al.*, 1998; Thomas *et al.*, 1999] images. The likely limited sand production in the Amazonian, combined with sand destruction and removal over time, should reduce the supply of sand available for abrasion. Particle threshold friction speeds were barely reached at the Viking 1 landing site [Greeley *et al.*, 1982] and apparently not reached at the Viking 2 site (even during dust storms [Ryan and Henry, 1979]) or the Pathfinder site [Schofield *et al.*, 1997]. Therefore, any sand surviving on Mars today that can be harnessed by the wind may saltate infrequently because of lower wind speeds. Threshold friction speed is inversely proportional to atmospheric density [Greeley *et al.*, 1976; Greeley and Iversen, 1985], so that sand was probably more effectively harnessed earlier in Martian history, when (and if) atmospheric pressures were greater. Consideration of all these factors strongly suggests that the sand supply and the effectiveness of sand as a weathering agent have decreased since the Hesperian. If this is correct, it may explain why the putative sand in the possible dunes identified by Greeley *et al.* [this issue] in the MOC image have not produced more erosion during the most recent climatic regime.

Our knowledge of the Martian surface layer developed from remote sensing observations, image analysis, and observations at the three landing sites agrees with the very slow erosion rates described above and suggest that since the Hesperian a surface layer of order meters to up to several tens of meters thick has been redistributed around Mars [Christensen and Moore, 1992]. This layer likely consists of sand and dust size particles that are entrained and moved by the wind [Greeley *et al.*, 1992]. Dust can be deposited and removed at much greater rates over short

time periods. As discussed earlier, dust was deposited on Pathfinder's solar panels at 5-15 $\mu\text{m}/\text{yr}$ [Landis and Jenkins, 1998, this issue] and redistribution rates similar to these have also been inferred from opacity observations during Viking and models of dust settling [e.g., Greeley *et al.*, 1992]. Other areas may be net sinks for this material, such as Amazonis Planitia, whose thermal inertia, radar, and imaging properties suggest meters thick accumulations of dust [Christensen and Moore, 1992]. Sand has also accumulated in the north polar erg, a large region of sand dunes surrounding the polar cap [Greeley *et al.*, 1992]. Other areas such as the Pathfinder landing site appear to have been swept clean or even deflated. The moderate bulk thermal inertia and fine component thermal inertia, the high rock abundance, and the low albedo and red-violet ratios in Viking remote sensing data for the Pathfinder landing site generally support this interpretation [Golombek *et al.*, 1997a, 1999]. The short term rates of deposition and removal and longer term redistribution rates of wind blown material in Late Hesperian and Amazonian time are of order meters per million years.

The observation that the current direction of the strongest winds towards the southwest in atmospheric circulation models agrees with the direction of wind tails at the Pathfinder site and nearby bright wind streaks in Viking orbiter images [Greeley *et al.*, 1999] could be used to argue that most of the deflation has occurred during the present 51,000 year climate cycle [Leovy, 1999]. If true, this would result in deflation rates as high as the redistribution rates cited above. However, the winds that formed the wind tails could have also occurred incrementally during multiple 100,000 years oscillations when the strongest wind direction was similar to today's and not just in the past 51,000 years. In addition, as discussed earlier, much of the deflation of the surface probably occurred during the earlier environment, when saltating sand carved most of the ventifacts. Furthermore, if recent erosion rates were as high as the redistribution rates, crater rims on relatively young surfaces would be planed off and erased in a comparatively short time (of order Ma). The freshness of crater rims observed from the Pathfinder lander and the general freshness of crater populations on similar aged surfaces on Mars argues that such high erosion has not occurred. Finally, even if deflation of the landing site occurred in the past 51,000 years,

then no net changes to the site have occurred for the previous 1.749-3.749 Ga, which results in the same long term erosion rates derived [Golombek, 1999b].

Early Warmer/Wetter Environment

In contrast to the desiccating environment of today, a variety of observations by Pathfinder support an earlier climate that was warmer and wetter. Rounded pebbles and cobbles [Rover Team, 1997], evidence for abundant sand-size particles discussed earlier, and possible conglomerates [Rover Team, 1997] observed at the Pathfinder landing site suggest an early fluvial environment that was warmer and wetter than today. Airborne dust particles collected by the Pathfinder magnetic targets further support this hypothesis [Hviid *et al.*, 1997; Madsen *et al.*, 1999]. The particles are composite silicates with a highly magnetic mineral interpreted to be maghemite (although other interpretations are also possible [e.g., Morris *et al.*, 1999]) that may have freeze dried as a stain or cement from liquid water that previously leached iron from crustal materials in an active hydrologic cycle. Sand-size particles appear to be abundant at the landing site and on Mars in general, as previously discussed. The inferred abundance of sand on Mars, which on Earth typically forms via water dominated weathering, erosional and depositional processes that mechanically break down rocks into smaller fragments [Kuenen, 1960; Krinsley and Smalley, 1972; Pettijohn *et al.*, 1987], may be another indicator of a warmer and wetter past. The suggestion that the early Martian environment was warmer and wetter is not new [e.g., Carr, 1996]. Valley networks (at least one of which, Nanedi Vallis, has a central fluvial channel, or thalweg, almost certainly formed by running water [Malin and Carr, 1999]) and associated dry lake beds [Baker and Partridge, 1986; Carr, 1996]; possible strand lines, beaches and terraces inferring a northern ocean [Parker *et al.*, 1993]; and rimless, degraded craters in ancient heavily cratered terrain [Craddock and Maxwell, 1993; Barlow, 1995; Grant and Schultz, 1993; Craddock *et al.*, 1997] have all been described in Viking Orbiter images and used to argue for a warmer and wetter past in which liquid water may have been stable with the environment.

Erosion Rates Through Time

Erosion rates from the literature and our result from the Pathfinder landing site shows a dramatic decrease with time (Table 1; Figure 8). Erosion rates calculated from changes in Noachian age crater numbers and shapes are 4-6 orders of magnitude higher ($0.1\text{-}10\text{ }\mu\text{m/yr}$ or $10^2\text{-}10^4\text{ nm/yr}$) [Craddock and Maxwell, 1993; Craddock et al., 1997; Carr, 1992] than those calculated for more recent times. Present day denudation rates for the Earth are as low as 2 B (but can range up to 10^3 B or more), where 1 B is a Bubnoff unit, which is equivalent to $1\text{ }\mu\text{m/yr}$ [Saunders and Young, 1983; Judson and Ritter, 1964] and thus are comparable to erosion rates during the Noachian on Mars. Estimates of erosion rates during different epochs of Martian geologic time also show a rapid decrease in erosion rate through time. Erosion rates during the Noachian are $10^2\text{-}10^4\text{ nm/yr}$, and close to short term rates (10^4 nm/yr) of aeolian redistribution of sand and dust on Mars [Arvidson et al., 1979; Greeley et al., 1992]. The redistribution rates are not the same as erosion rates because they likely indicate the horizontal motion of already liberated aeolian material, rather than the erosion and subsequent deposition of new material. Estimated erosion rates are inversely proportional to the time period over which they are averaged, with Noachian and Hesperian rates of $10^2\text{-}10^3\text{ nm/yr}$ [Craddock et al., 1997] and rates of $10^{-1}\text{-}10^1\text{ nm/yr}$ that include the Hesperian through the present [Carr, 1992; Arvidson et al., 1979]. The Hesperian to recent estimates of erosion or redistribution are from the possible deflation of the Viking 2 landing area [Arvidson et al., 1979] and the partial filling in of craters since the Early Hesperian [Carr, 1992]. Possible thickness changes of order tens of meters in the past 3.5-3.8 Ga loosely constrains erosion and/or redistribution rates to $<0.02\text{ }\mu\text{m/yr}$ [Carr, 1992]. These results indicate that erosion rates during the Hesperian are much lower (by 3-5 orders of magnitude) than those during the Noachian. Erosion rates from the Hesperian are probably closer to $10^{-1}\text{-}10\text{ nm/yr}$, as the higher estimate likely includes redistributed material, so may be slightly inflated [Carr, 1992]. Erosion rates during the Amazonian from the Pathfinder site are even lower at 10^{-2} nm/yr .

The rapid decrease in erosion rates are consistent with a major climatic change on Mars. The higher estimates of erosion rates during the Noachian (greater than a few B) are comparable

to slow continental denudation rates on the Earth in a variety of warm climatic regimes [*Saunders and Young*, 1983; *Judson and Ritter*, 1964], which is consistent with erosion by running water suggestive of a more clement climate. Extremely slow erosion rates since the Hesperian are consistent with the current cold and dry environment. These results are also consistent with the possibility that most sand and dust formation on Mars occurred during the Noachian, with this material simply being redistributed since.

Constraints on when the suggested climate change occurred are not tightly bound due to uncertainties in the proposed crater density time scales (see discussion by *Tanaka*, [1986] of the crater time scales proposed by *Neukum and Wise* [1976] and *Hartmann et al.* [1981]). The highest erosion rates occurred during the Noachian. Erosion rates during the Amazonian and preferred rates during the Hesperian are substantially lower, so that the current cold and dry climate could date back to end of the Noachian/beginning of the Hesperian, estimated to be 3.5-3.8 Ga [*Tanaka*, 1986]. All three landers are on units of Early Amazonian to Middle Hesperian age and thus appear to document the modern dry, desiccating environment since the Middle Hesperian, 3.1-3.7 Ga [*Tanaka*, 1986]. Valley networks, the most obvious features suggesting higher erosion rates, appear to be dominantly Noachian in age [*Baker et al.*, 1992; *Carr*, 1996]. The impact degradation of many valley networks further suggests that they may have formed at the tail end of heavy bombardment around 3.9 Ga [*Baker and Partridge*, 1986; *Schultz and Britt*, 1986]. As a result, a possibly warmer and wetter climate on Mars may have survived only a few hundred million years after heavy bombardment ended and may have been replaced by a climate similar to today's at that time.

CONCLUSIONS

1) Pathfinder observations of streamlined hills, the ridge-trough rocky surface, perched, imbricated, and subrounded tabular rocks, and a surface analogous to catastrophically deposited fans on Earth argue for the site being little altered since it formed in Late Hesperian/Early Amazonian time, 1.8-3.5 Ga.

2) Sculpted wind tails, an exhumed former soil horizon, ripplelike and other lag deposits, and ventifacts indicate the landing site has been deflated by 3-7 cm. The wind direction responsible for the orientation of the wind tails and dunes is towards the southwest, similar to present day atmospheric circulation models and similar to nearby bright wind streaks behind craters in Viking Orbiter images. In the present climate, sand appears to be trapped in lows and/or rarely harnessed by the wind.

3) Barchan dunes and ventifacts argue for erosion by saltating crystalline sand-size particles entrained in the wind. The orientation of most ventifacts suggests winds blowing towards the northwest, which also were responsible for northeast-southwest oriented dunes in Big Crater, and possibly for suggested preferential erosion of small crater rims. Most ventifacts were probably carved soon after catastrophic flooding, which introduced a fresh, widely distributed supply of sand-size particles that were easily harnessed by the wind. Wind speeds must have been above the threshold wind speed for saltation and the saltating sand likely effectively eroded and deflated the surface.

4) Deflation rates responsible for the erosional features at the Pathfinder landing site are extremely low, 0.01-0.04 nm/yr since the end of the Hesperian, 1.8-3.5 Ga. Less precise estimates based on the preservation of impact crater rims in view of the Viking and Pathfinder landers limits erosion rates to <1 nm/yr for the Hesperian and Amazonian epochs. Atmospheric dust was observed to be deposited on the Pathfinder lander at rates as high as 10^5 nm/yr, which over longer time scales must be removed (perhaps by the frequent dust devils observed), or the surface would be buried under meters thickness of dust in a comparatively short million years. Rates as high as these have also been suggested for the aeolian redistribution of sand and dust making up the Martian surface layer since the Hesperian.

5) Estimates of erosion rates through time show a dramatic drop by 4-6 orders of magnitude from the Noachian to the Hesperian/Amazonian. Highly eroded Noachian terrain, characterized by rimless, shallow, flat floored craters and valley networks have erosion rates of 10^2 - 10^4 nm/yr, compared to extremely low erosion rates of 10^{-2} nm/yr for the Amazonian.

Noachian rates are comparable to low continental denudation rates on the Earth, which is consistent with erosion by running water and a more clement climate. Extremely slow erosion rates since the Hesperian are consistent with the current cold and dry environment. The possible climate change probably occurred in the Noachian, before 3.5-3.8 Ga, consistent with a warmer and wetter environment surviving only a few hundred million years after the end of heavy bombardment and being replaced by a climate similar to today's.

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Table 1. Summary of Erosion Rates through Time on Mars

Epoch	Erosion Rates	
	(nm/yr)	μm/yr, Buhroff units, B
Amazonian through Present	10^{-2}	0.00001-0.00004
Hesperian through Present	$10^{-1} - 10^1$	0.0001-0.02
Noachian through Hesperian	$10^2 - 10^3$	0.1-5
Noachian	10^2-10^4	0.3-10

FIGURE CAPTIONS

Figure 1: Image of rocks about 3 m southwest of the lander in the Rock Garden showing possible exhumed soil horizon (portion of IMP superpanorama sequence 184). Black arrows point to horizons on the rocks Flat Top (left) and Little Flat Top (right). White arrow shows possible horizon on the rock Stimpy. Image has been processed to bring out detail. Note the different appearance of this red band from the dusty tops of rocks.

Figure 2: Image of the rocks Ender, middle, and Hassock, right, about 4 m to the southwest of the Pathfinder lander. The lower part of Ender (black arrow) shows a bright, pebble-rich layer that extends to the right, where it is about 7 cm above the surface. The presence of pebbles in this layer argues that it is a remnant of a thicker surface layer, in which the finer sand and dust has been mostly removed (slightly more pebble rich than the lower adjacent pebbly soil surface). These features and the 5-7 cm thick reddish former soil horizon argues that the site has been deflated or exhumed by the wind since deposition. The image was acquired through the 750 nm filter and is stretched and sharpened to bring out detail (image ID 0185020175).

Figure 3: Ripples are composed of alternating bands of pebbles and relatively pebble-free zones that are interpreted to be lag deposits. The pebbles average about 5 mm in diameter and the

ripples have wavelengths of ~3-6 cm. View looking toward the northwest (azimuth ~320°). Uncompressed images acquired through the 440, 530, and 750 nm filters to produce color were acquired when the camera was in its pre-deployed position and, as such, generally display details of topography and small-scale roughness better than images taken from the deployed position. The images have been stretched and sharpened to bring out detail.

Figure 4: Wind tails are located on the left side of rocks and taper toward the left, indicating winds blowing towards the left, or southwest, direction (image looking toward the west, azimuth ~290°). The sharp edges of the tails and their sculpted narrow appearance suggests they are erosional features. The most prominent tail is seen next to the lower edge of the rock Barnacle Bill in the right part of the image. It is 35 cm long and 3 cm high next to Barnacle Bill. Color image was produced by combining images acquired through the 440, 530, and 750 nm filters and are uncompressed. The images were acquired in the pre-deployed position and have been stretched and sharpened to bring out detail.

Figure 5: Rover close up image mosaic from the left front camera of the rock Moe, showing fluted and grooved surface indicative of ventifacts. The formation of ventifacts at the Pathfinder site argues for erosion by saltating, crystalline sand-size particles. This is the most abraded rock identified at the landing site, with smaller flutes within larger flutes. Prominent flutes seen here average about 10 cm long and 2 cm wide. The scale bar corresponds to 10 cm at the back edge of the rock. The mosaic is stretched and sharpened to bring out detail (images 1252882263 and 1252882692).

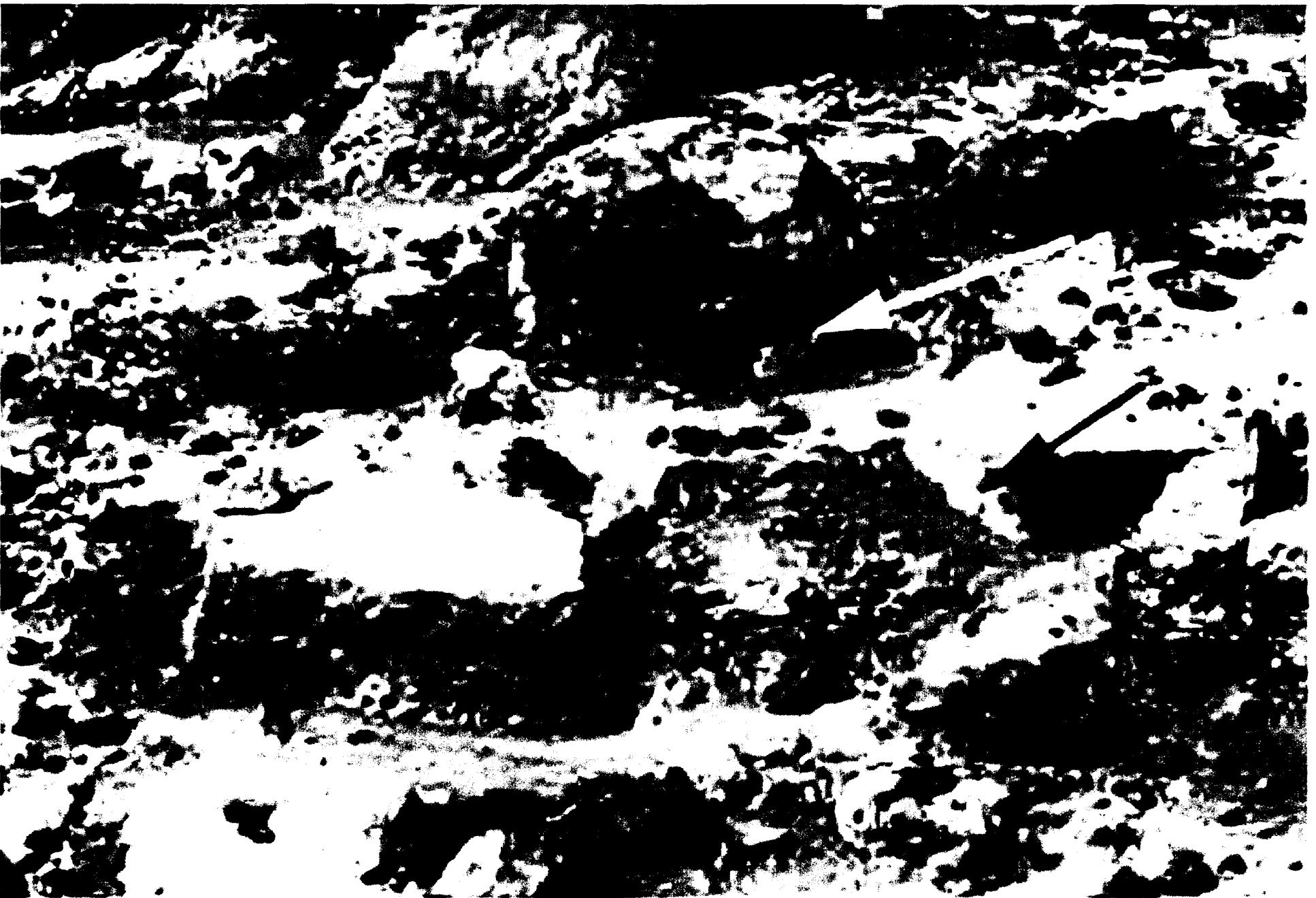
Figure 6: Rover image mosaic from the right front camera of barchan dunes in a trough about 12 m southwest of the lander, behind the Rock Garden. These dune forms are most likely composed of sand-size particles deposited by aeolian saltation. The prominent duneform in the foreground is ~15 cm high at its midpoint and ~1 m long. The horns point to the southwest indicating that the winds forming these dunes blew towards the southwest (view is looking toward the west-northwest). Sand saltates up the stoss side of the dunes (right side) to the lee, or slip face, of the dunes to the left. Barchans generally form in regions of limited

sand supply that are subjected to unidirectional winds. The Twin Peaks are visible in the background. The mosaic is stretched and sharpened to bring out detail (images 1253411891 and 1253412760).

Figure 7: Mars Orbiter Camera image of the Pathfinder landing site (portion of image #25603, about 3.3 m/pixel, with an effective resolution of about 5 m/pixel due to haze). Double-sided black arrow shows the longitudinal trend of bright ridges. Single-sided black arrows point to possible eroded northwest rims of craters [Greeley *et al.*, 1999]. White arrow points to dunes within Big Crater. Pathfinder landing site is marked by an X. BC is Big Crater, LC is Little Crater, NK is North Knob, RC is Rimshot Crater, TP are Twin Peaks. Image has been processed to bring out detail and is geometrically rectified to simulate a nadir view.

Figure 8: Compilation of rate of change (in nm/yr; 1000 nm/yr = 1 μ m/yr = 1 B) of landscapes on Mars through time. Noachian (>3.5-3.8 Ga), Hesperian (1.8-3.5 Ga or 2.5-3.8 Ga) and Amazonian (1.8 Ga or 3.5 Ga to present) time periods on Mars are indicated. Dashed lines are estimates assuming *Neukum and Wise* [1976] time scale, which tends to make epochs older and solid lines assume *Hartmann et al.* [1981] time scale, which tends to make epochs younger, as modified by *Tanaka* [1986]. Vertical line with filled square end points marked "Dust" are deposition rates of dust on the Pathfinder solar panels [Rover Team, 1997; Landis and Jenkins, 1998] and dust estimated to fall out of the atmosphere as summarized by *Greeley et al.* [1992]. These dust deposition rates are similar to rates of aeolian redistribution elsewhere on Mars [Arvidson *et al.*, 1979]. Vertical line with filled triangle end points marked "Earth" are slow denudation rates on Earth [Saunders and Young, 1983; Judson and Ritter, 1964]. Key to estimates: open circles are from *Craddock and Maxwell* [1993] and *Craddock et al.* [1997]; open squares are from *Carr* [1992]; open diamonds are from *Hartmann et al.* [1999]; open triangles are from *Arvidson et al.* [1979], with possible erosion recalculated since the beginning of the Late Hesperian as shown in *Tanaka* [1986]. Lines without symbols are from this work. Rates since the end of the Noachian from *Carr* [1992] (gray line with open squares) are likely inflated because they include redistributed material.

Golombek + Bridges
In Color



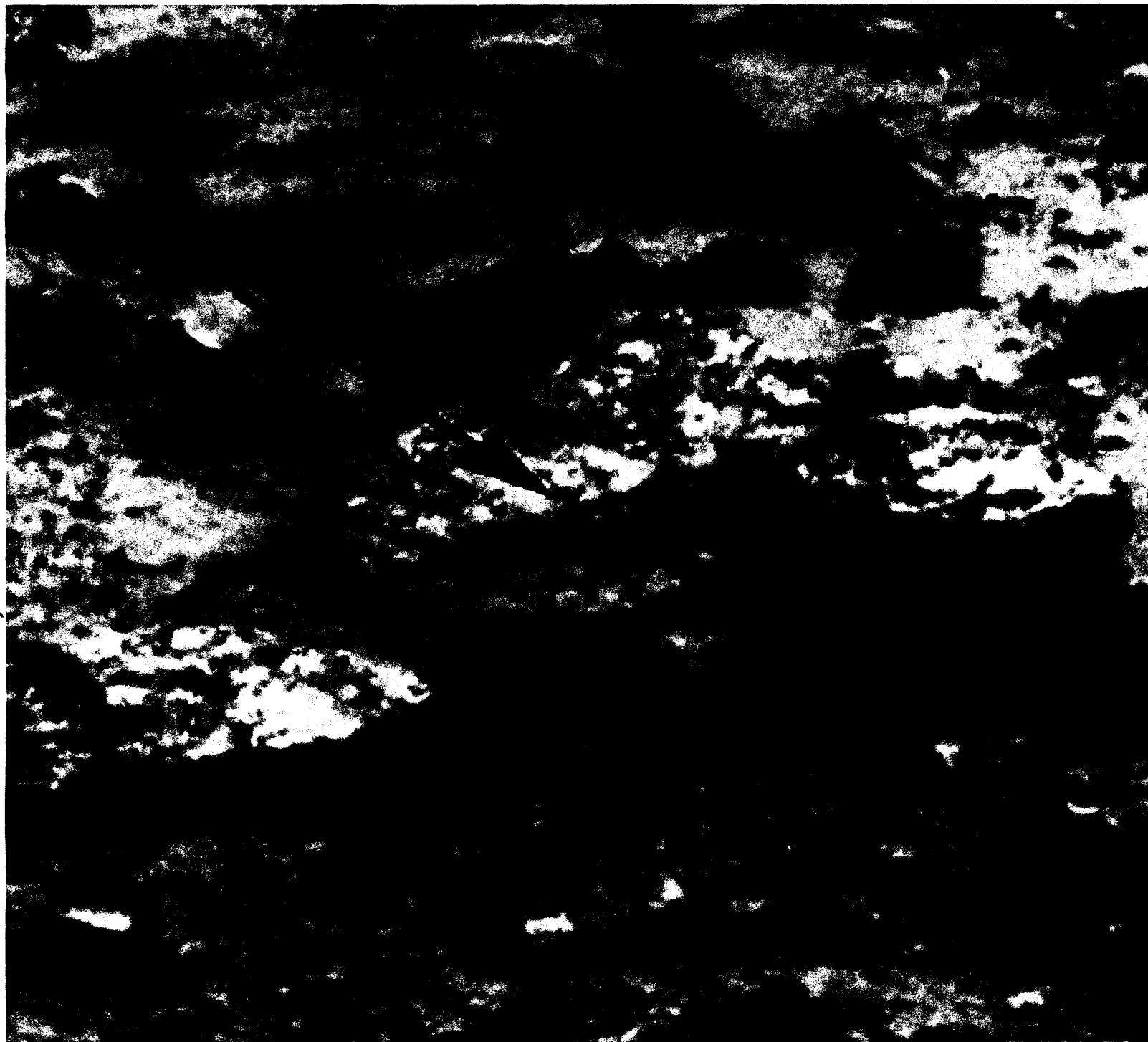


Figure 2

Golombek +
Bridges

In Color



Figure 3
Golombek +
Bridges
In Color



Figure 4
Golombek +
Bridges
In Color



Figure 5
Golombek +
Bridges

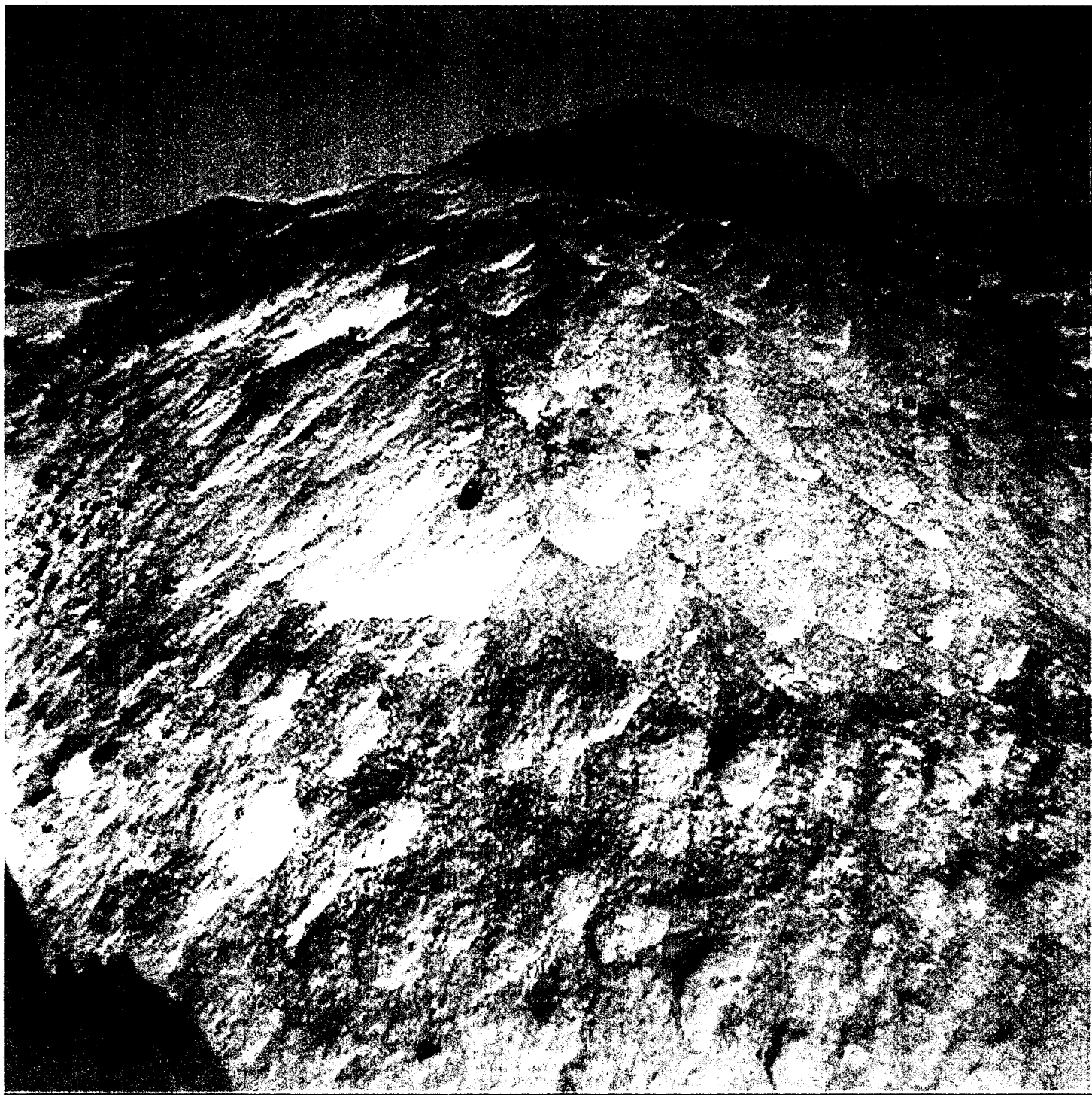


Figure 6
Golombek +
Bridges



Figure 7
Golombek
+
Bridges

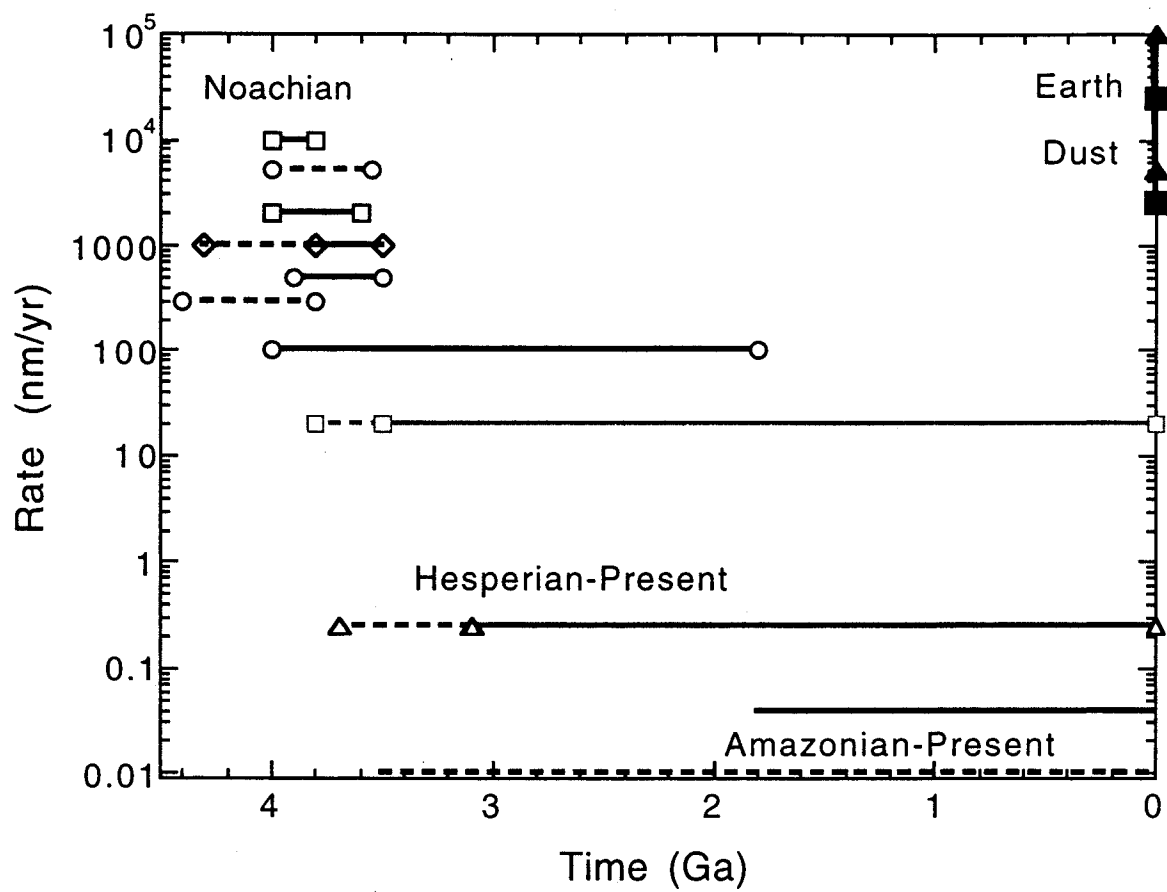


Figure 8